THERMAL COMFORT IN A CLOSED SPACE BASED ON CLOSED LOOP TEMPERATURE CONTROL

A PROJECT THESIS SUBMITTED IN THE FUFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

BY

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UNDER THE GUIDANCE OF

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NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA

2009-2010

Declaration

This is to certify that the work in this Thesis Report entitled "THERMAL COMFORT IN A CLOSED SPACE BASED ON CLOSED LOOP TEMPERATURE CONTROL" by R Abhishek and R Balachander has been carried out under my supervision in partial fulfillment of the requirements for the degree of Bachelor of Technology, during session 2009-2010 in the Department of Electrical Engineering, National Institute of Technology Rourkela, and this work has not been duplicated as far my knowledge goes.

Place: Rourkela

Date:

Prof. P K SAHU

Department of Electrical Engineering

NIT Rourkela

Acknowledgement

It is with great satisfaction and pride that we present our thesis on the project undertaken under the “Research Project” paper during 7th and 8th semesters, for partial fulfillment of our Bachelor of Technology degree at NIT Rourkela. We are thankful to **Prof. P K Sahu** for being our mentor during this endeavor. He has been the corner stone of our project and has guided us during periods of doubts and uncertainties. His ideas and inspirations have helped us make this nascent idea of ours into a fully fledged project. We are also thankful to all the professors of our department for being a constant source of inspiration and motivation during the course of the project. We offer our heartiest thanks to our friends for their constant inspirations and their help in collection of data samples whenever necessary. Last but not the least, we want to acknowledge the contributions of our parents and family members, for their constant motivation, inspirations and their belief in us that we could make it happen.

R Abhishek

R Balachander

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Abstract

In modern office buildings, the common trend is to use state of the technology to ensure the users to get thermally comfortable in order to produce maximum work efficiency. From the statistical studies so far on comfort index vs. work efficiency of users, the most widely adopted index is the **Predicted Mean Vote (PMV)**. Based on this index, this work proposes a control scheme on neural network and fuzzy logic, for modifying the environmental conditions of a closed indoor space, by regarding not only the climatic indoor variables but also the activity level and clothing index of the space users. In this work along with temperature control the speed of the fan has also been taken into consideration.

CHAPTER 1

Introduction

1.1 Introduction

A healthy and comfortable thermal environment of indoor workspace helps the users to improve their work efficiency by maintaining various comfort related parameters within the desired range. Human comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment” [1]. Thermal comfort is affected by heat conduction, convection, radiation, and evaporative heat loss. Thermal comfort is maintained when the heat generated by human metabolism is allowed to dissipate, thus maintaining thermal equilibrium with the surroundings. Any heat gain or loss beyond this generates a sensation of discomfort. It has been long recognized that the sensation of feeling hot or cold is not just dependent on air temperature alone. Many researches works on many indexes for the calculation of thermal comfort, one of the most widely used methods is the predicted mean value (PMV) index [2]. It takes into account all the parameters such as air temperature, mean radiant temperature, relative air velocity, humidity, activity level and clothing thermal resistance.

In this work neural network and fuzzy logic based controllers has been used as the tool to mainly control the temperature with the use of PMV index as the control parameter.

1.2 Thesis layout

In Chapter 2:

The concepts regarding calculation of PMV are discussed. The various parameters effecting thermal comfort has been explained.

In Chapter 3:

This chapter consists of the three proposed models for the controller.

In Chapter 4:

The analysis of the proposed models and the description of the key parts of the models.

In Chapter 5:

The results obtained from the test inputs to various models and the comparison based on the results obtained.

Chapter 2

Overview of PMV

2.1 PMV

The **Predicted Mean Vote** or **PMV index** predicts the mean response of a large group of people according to the following thermal sensation scale [3]:

+3 hot

+2 warm

+1 slightly warm

0 neutral

-1 slightly cool

-2 cool

-3 cold

When the PMV index value is zero, the conditions are most favourable and the comfort level is maximum. But, the conditions within the PMV range of -0.5 to +0.5 are acceptable i.e. PPD (Percentage of People Dissatisfied) index is 5% which is the least in this range.

2.2 Equation of PMV

Fanger [2] has related PMV to the imbalance between the actual heat flow from the body in a given environment and the heat flow required for optimum comfort at the specified activity as stated by the following equation

The relation of PMV to the imbalance between the actual heat flow from body in an environment and the heat flow required to maintain the thermal comfort has been shown by Fanger using the following equation:

$$PMV = (0.303 \times e^{-0.036M} + 0.028)\, l$$

Here,

$$L=[\ (M\text{-}W) - 3.05 \times 10^{-3}\ \{5733 - 6.99(M\text{-}W)\text{-}p_a\} - 0.42\{\ (M\text{-}W) -58.15\ \} - 1.7\text{x}10^{-5}M(5867\text{-}\ p_a) - 0.0014M(\ 34 - t_a) - 3.96\text{x}10^{-8}\{(t_{cl}+273)4 - (t_{mr} + 273)\} - f_h h_c(t_{cl}\text{-}t_a)\ ]$$

$$t_{cl} = 35.7 - 0.028(M\ \text{-}W) - 3.96 \times 10\text{-}8f_{cl}[(t_{cl} + 273)4 - (t_{mr} + 273)4] - f_{cl}h_c(tcl - ta)\ [4]$$

$$h_c = \begin{cases} 2.38\ (\ t_{cl} - t_a\ )^{0.25} & \text{for } 2.38\ (\ t_{cl} - t_a\ )^{0.25} > 12.1\sqrt{Va} \\ 12.1\sqrt{Va} & \text{for } 2.38\ (\ t_{cl} - t_a\ )^{0.25} < 12.1\sqrt{Va} \end{cases}$$

$$f_{cl} = \begin{cases} 1 + 0.2I_{cl} & \text{for } I_{cl} < 0.5 \text{ clo} \\ 1.05 + 0.1I_{cl} & \text{for } I_{cl} > 0.5 \text{ clo} \end{cases}$$

PMV : Predicted Mean Vote
M : Metabolism, W/m^2
W : External Work
I_{cl} : Thermal resistance of clothing, clo
f_{cl} : The ratio of surface area of clothed body to the surface area of the nude body
t_a : Air temperature, ^{o}C
V_a : Relative air velocity, m/s
p_a : Water vapour pressure, pa
h_c : Convective heat transfer coefficients, W/m^{2}K
t_{cl} : Surface temperature of clothing, ^{o}C

2.3 Parameters Used in PMV

The PMV index includes six different parameters in order to calculate the comfort level. Four of these are the environmental parameters and the other two are the human parameters.

2.3.1Metabolism (M)

Energy is released by various processes in the body. The rate at which this energy is produced is according to the rate at which the body requires energy. This rate at which energy is supplied is called metabolism. The value for metabolism can vary from 47 W/m^2 (when lying down) to as high as 175 W/m^2 (in case of heavy activity like garage work).

In this work the value of metabolism has been taken as 58.15 W/m^2 (working lightly while sitting).

2.3.2External work (W)

This refers to the energy that is required in order to overcome the resistances offered during the work performed by a person. The value of W can be both positive and negative depending upon the type of work.

In this work we have considered the case of light work being performed while sitting. Hence the value of W would be zero.

2.3.3Mean Radiant Temperature (t_{mr})

Technically, MRT is defined as the uniform temperature of a surrounding surface giving off blackbody radiation (emissivity e = 1) which results in the same radiation energy gain on a human body as the prevailing radiation fluxes which are usually very varied under open space conditions.

But in this study the absolute temperatures of objects are large compared to the temperature differences. So, the Mean radiant temperature (MRT) is simply the area weighted mean temperature of all the objects surrounding the body.

$$\mathbf{t_{mr} = \frac{A_1 t_{s1} + A_2 t_{s2} + \ldots\ldots + A_6 t_{s6}}{A_1 + A_2 + \ldots. + A_5 + A_6}}$$

Here

tsi : Surface temperature of the walls

Ai :Surface area of the walls

2.3.4 Water Vapour Pressure (Pa)

The vapour pressure of water is the vapour pressure (or equilibrium/saturation pressure) of water, i.e., the pressure exerted by water at a specific temperature. This is the parameter that affects the relative humidity of a particular area. The value of Pa can be calculated according to the formula:

$$\mathbf{P_a = exp(20.386 - 5132/T)}$$

Here

Pa : Water vapour pressure

T :temperature in kelvins

2.3.5 Speed of indoor air (V_a)

The speed of the air is also one of the important factors that affect the thermal comfort in a space. In this study we have considered that the windows and the doors are closed and hence we have taken the speed of the air to be 0.1 m/s.

In case the doors and windows are open the effect of the wind patterns, drafts, etc. has to be taken into consideration.

2.3.6 Thermal resistance of clothing (I_{cl})

The thermal resistance of clothing refers to the insulating abilities of the garments from the external environment. This depends on the type of the cloth on is wearing. Thicker the cloth higher is the thermal resistance of the clothing. This unit is measured in **clo**.

In this study we have considered the case of a corporate office where people will have to wear heavy suits and formal dresses to work. Hence we have taken the value of I_{cl} between 1clo to 1.7 clo.

Chapter 3

Proposed Models

The basic control model for the temperature control is as shown in the figure:

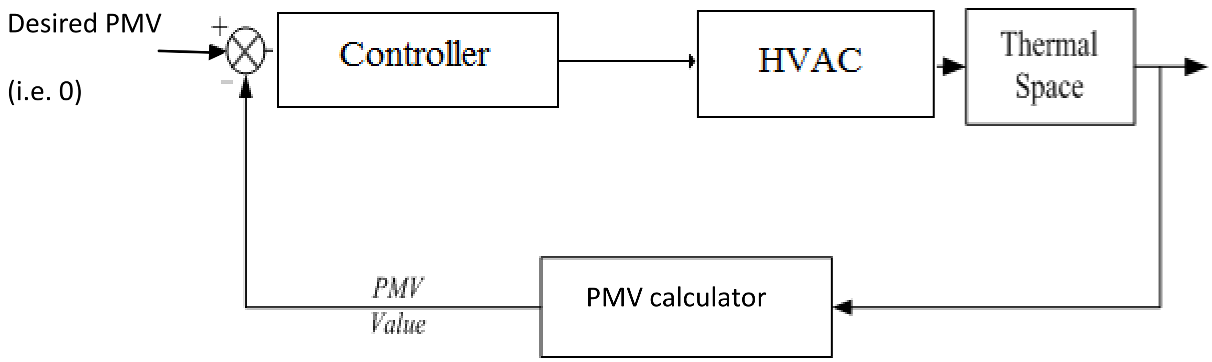

Fig 1. Model used for temperature control

The thermal space is the area where the temperature control has to be performed.

The thermal sensation model is the block that calculates the PMV taking into account various parameters from the thermal space.

HVAC is the component that consists of a cooler, heater and the fan in order to pump the air to the thermal space with the desired effect (i.e. heating or cooling).

The controller is the key part of the model that will limit the temperature within the required range according to the various conditions within the thermal space. The controller provides the signal for the selection of heater or cooler and controls the speed of the fan depending on the calculated PMV index.

Based on various approaches three models have been proposed as follows.

3.1Model 1:

This model is a neural network based model. In this model by controlling the fan speed the temperature of the room is controlled. In this model the calculated PMV index is converted into binary using the binary converter that gives the outputs X1, X2 and X3.

The output X1 is used to decide the temperature action to be taken i.e. the heating or the cooling action.

The outputs X2, X3 are used to control the speed of the fan in the HVAC using the neural network.

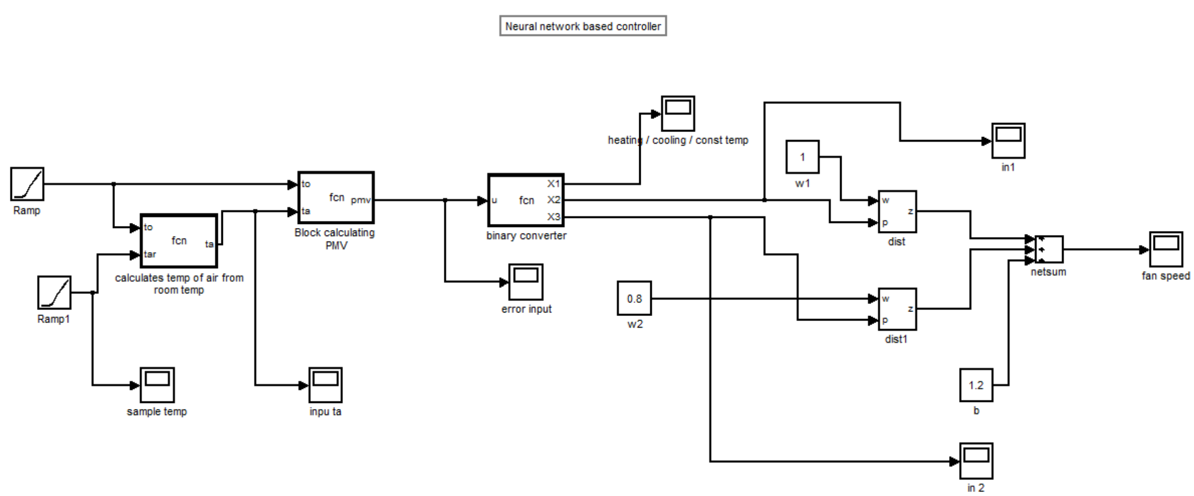

Fig 2. Model 1 (Neural Network Model)

3.2Model 2:

This only difference between this model and the previous model is that this uses fuzzy approach for the temperature control. The calculated PMV index is fed to the fuzzy logic controller and according to the PMV an output signal consisting of data about both the temperature action and fan speed is produced which is passed through a demux and the signals are separated.

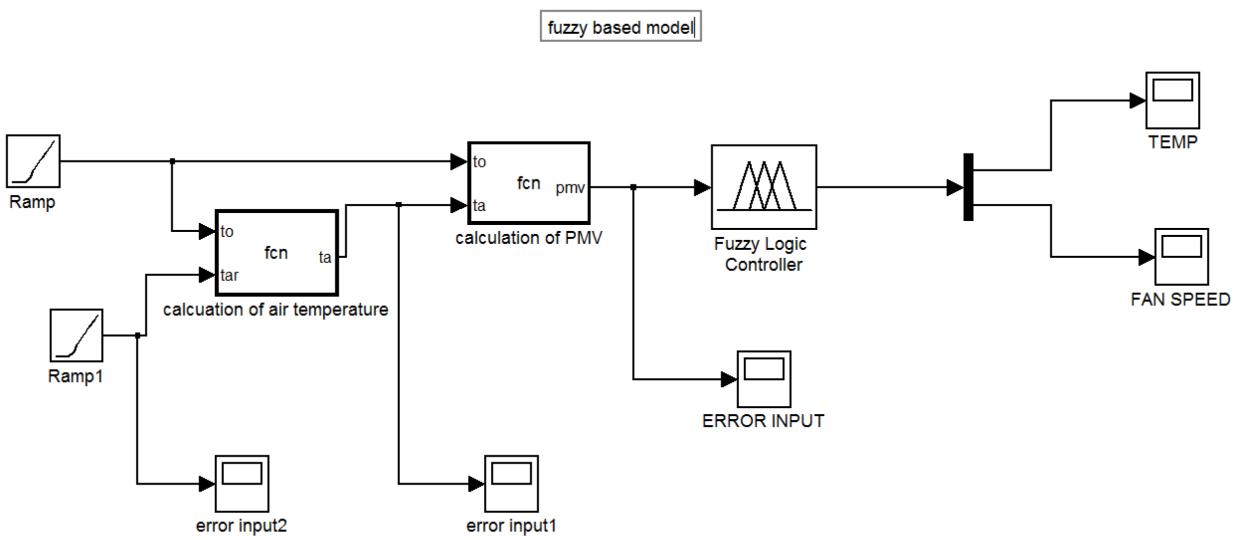

Fig 3. Model 3 (Fuzzy model)

3.3Model 3:

In this model according to the outside temperature a desired temperature for the air is calculated by the blocks air temperature and the reference temperature calculator, which is sent to the HVAC.

The signal for the fan speed is decided on the basis of the error between the reference temperature and the actual air temperature.

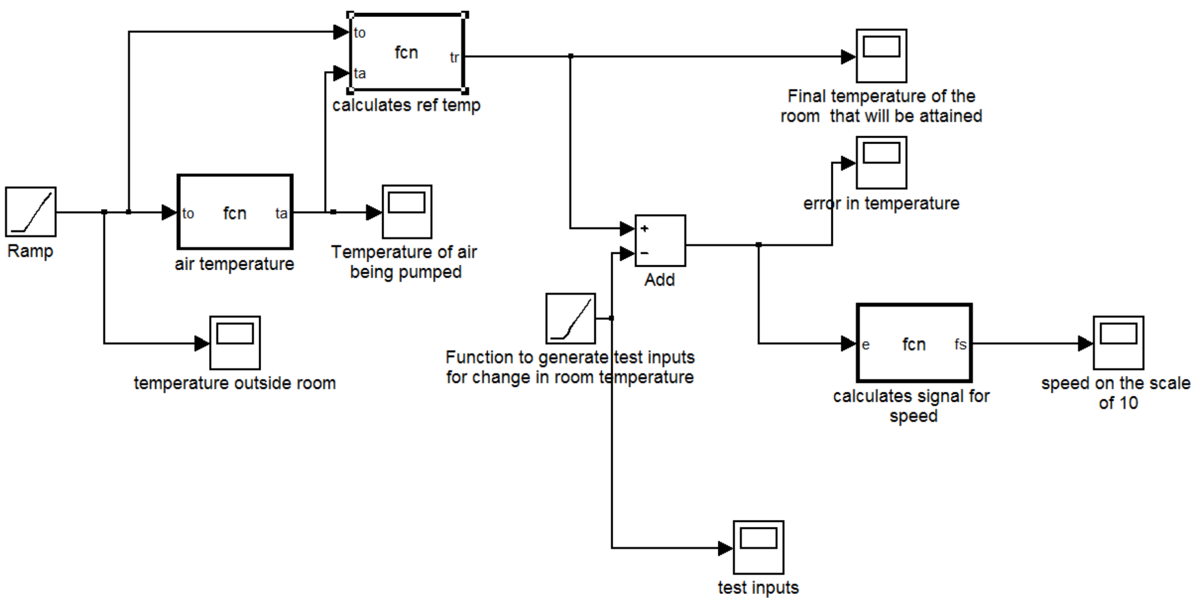

Fig 4. Model 3

Chapter 4

Analysis of the Proposed Models

4.1 Analysis of Model 1:

The neural network that has been used in the controller is the perceptron model that is mainly used to control the fan speed. By controlling the fan speed the temperature will be controlled.

4.1.1 Training Algorithm

The **training algorithm** that has been used is as follows:

1. The desired values of the output corresponding to the inputs were stored in the D matrix.
2. Initial weights and bias were declared zero.
3. Rate of learning (a) was set to 0.2.
4. Then the weights were calculated according to the formula:

   $$\mathbf{W_{in} = W_{io} + (a\, D_i\, X_i)}$$

   W_{in} : New value of weight calculated for i^{th} iteration.

   W_{io} : Value of the weight from $(i-1)^{th}$ iteration.

   X_i : Input for i^{th} iteration

   a : Learning rate

   D_i : Desired output corresponding to input for i^{th} iteration

5. The bias were calculated according to the formula:

   $$\mathbf{B_{in} = B_{io} + (a\, D_i)}$$

   Bin : New value of bias calculated for i^{th} iteration

   Bio : Value of bias from $(i-1)^{th}$ iteration

a : Learning rate

D_i : Desired output corresponding to input for i^{th} iteration

6. Step 5 and 6 were repeated for all the input and output sets and according to that final values of weight and the bias were decided that has been used in the model.

4.1.2Binary converter

The binary converter is an important aspect of this model. The outputs given by this block is used as the input for the neural network to calculate the fan speed. The algorithm for the binary converter is as follows:

1. The PMV inputs were quantized according to the required quantization levels.
2. Then the functions were defined to calculate the binary output according to the given quantized input. The function selects the proper output from the set of outputs according to the given input.

4.1.3Block to calculate air temperature

This is the block that calculates the air temperature in the room from the actual room temperature according to the formula:

$$\mathbf{T_a = (T_r(1 + \sqrt{10\,Va}\,)\; - Tmr)/ \sqrt{10\,Va}}$$

T_a : Temperature of the air

T_r : Temperature of the room

T_{mr} : Mean radiant temperature

V_a : Velocity of air

4.2 Analysis of Model2

As mentioned earlier this model is similar to the model 1 but, in model 2 we have used **Fuzzy Controller** instead of the neural network controller to control the speed of the fan.

4.2.1 Fuzzy Logic Controller

The fuzzy model that has been used in the controller is the **MAMDANI MODEL.**

The membership functions or the rule sets defined for the model is as follows:

Input:

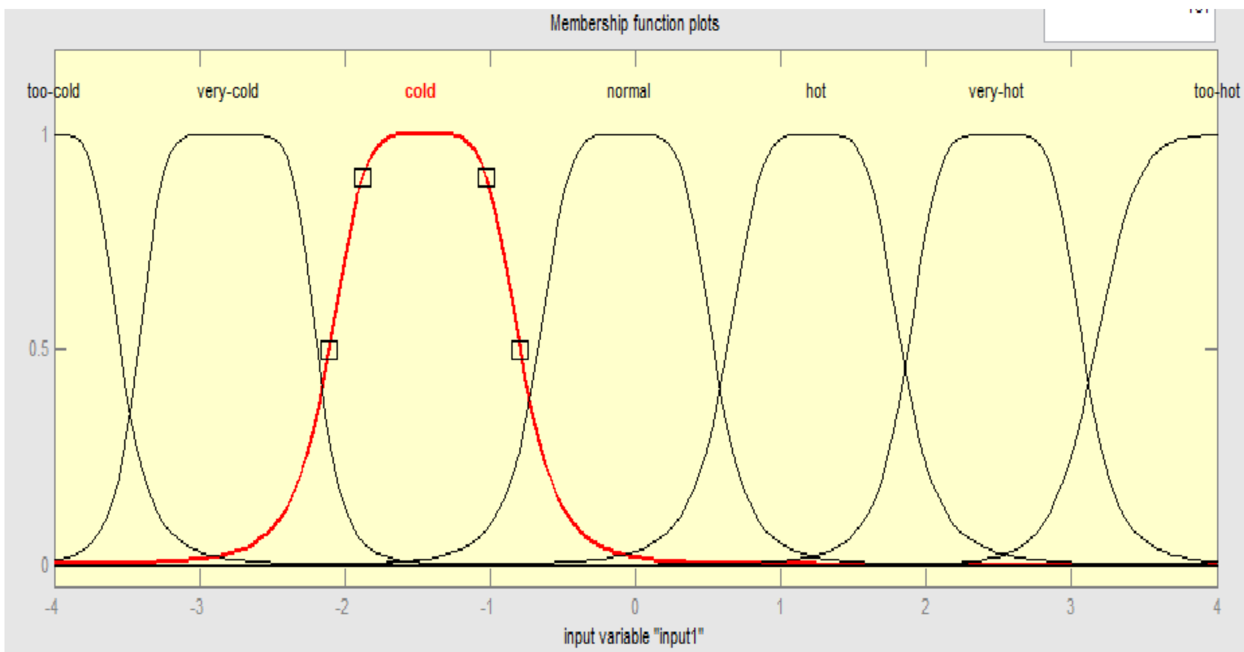

Fig 5. Input (Rule base)

Output:

Output1 (Temperature Action):

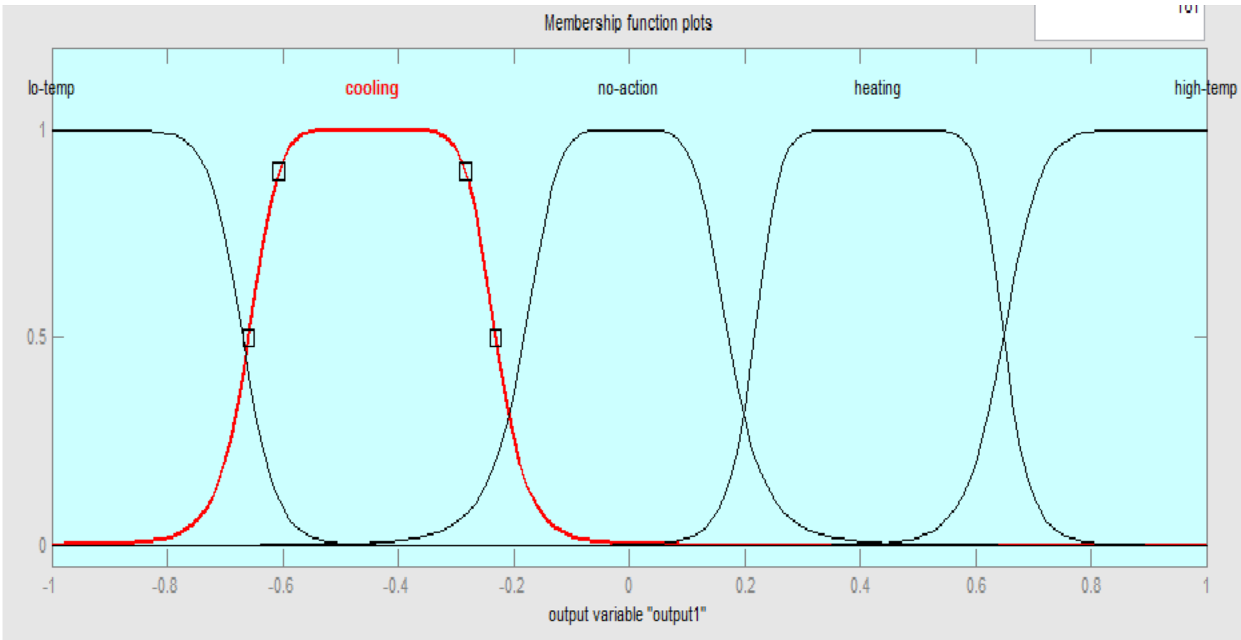

Fig 6. Output temperature action(Rule base)

Output2 (Fan Speed):

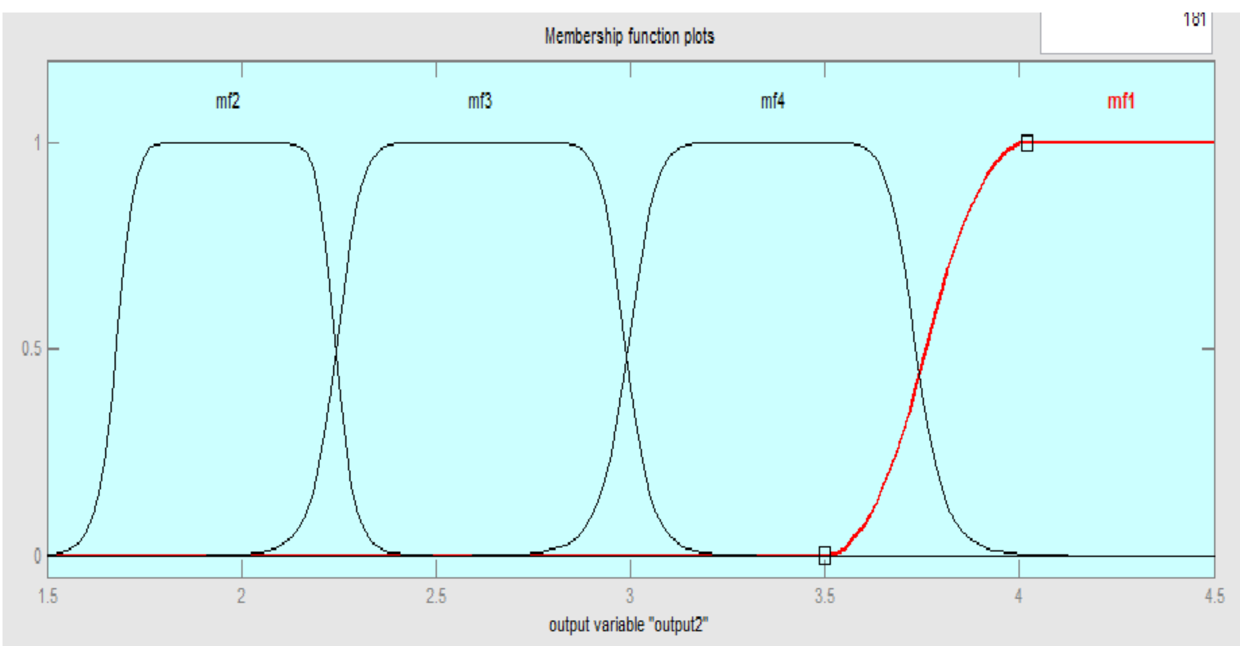

Fig 7. Output Fan speed(Rule base)

The fuzzy logic controller compares the input with the rule base input.

According to the rule base the output is generated for the **temperature action** and the **fan speed**.

4.3 Analysis of Model3

This model is mainly divided into two parts:

1. Calculation of the reference temperature.
2. Control of the fan speed.

4.3.1 Calculation of reference temperature

The reference temperature is the temperature of the room that will be attained finally when the PMV index for the thermal space would be zero.

The algorithm for the calculation of the reference temperature is as follows:

1. The temperature of the air that correspond to the PMV value 0 is calculated using the block "AIR TEMPERATURE" with the outside temperature as the input.
2. Then the reference temperature is calculated according to the formula:

$$\mathbf{T_r = (T_a \sqrt{10\ Va} + T_{mr}) / (1 + \sqrt{10\ Va})}$$

Tr	: Referance temperature
Ta	: Air Temperature
Tmr	: Mean Radiant Temperature
Va	: Velocity of air

4.3.2Control of fan speed

The error (i.e. the difference between the reference room temperature and the actual room temperature) is used as the input to generate the output for the fan speed on the scale of 10.

The fan speed varies linearly with the error values. Higher the value of error higher is the speed and lower the value of error lower is the speed.

Chapter 5

Results and Discussion

5.1 Results for Model1

5.1.1 Response of the system for different values of PMV

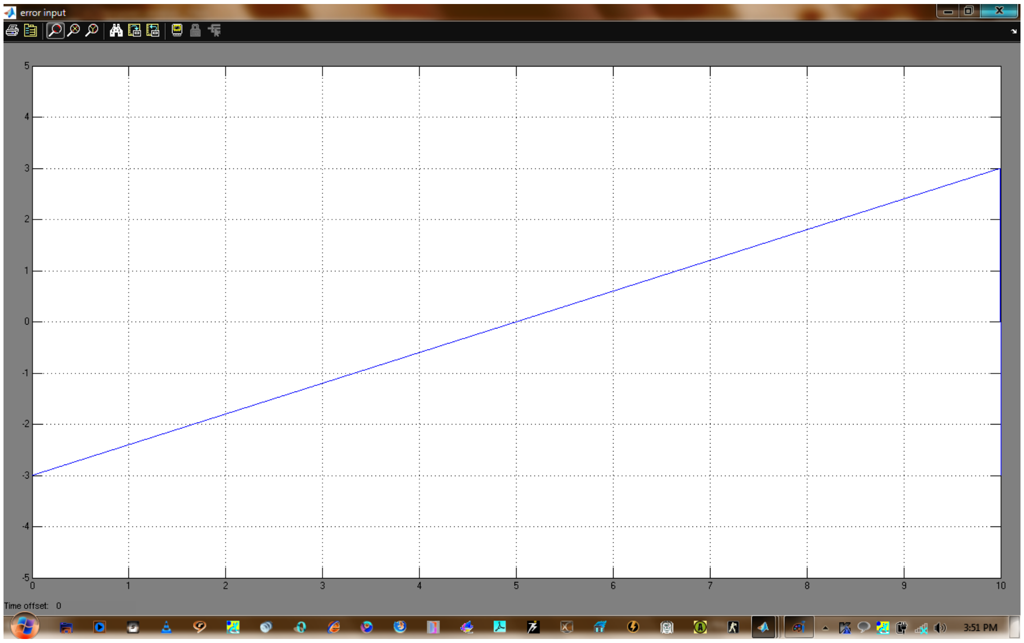

Fig 8. Test input: Different values of PMV

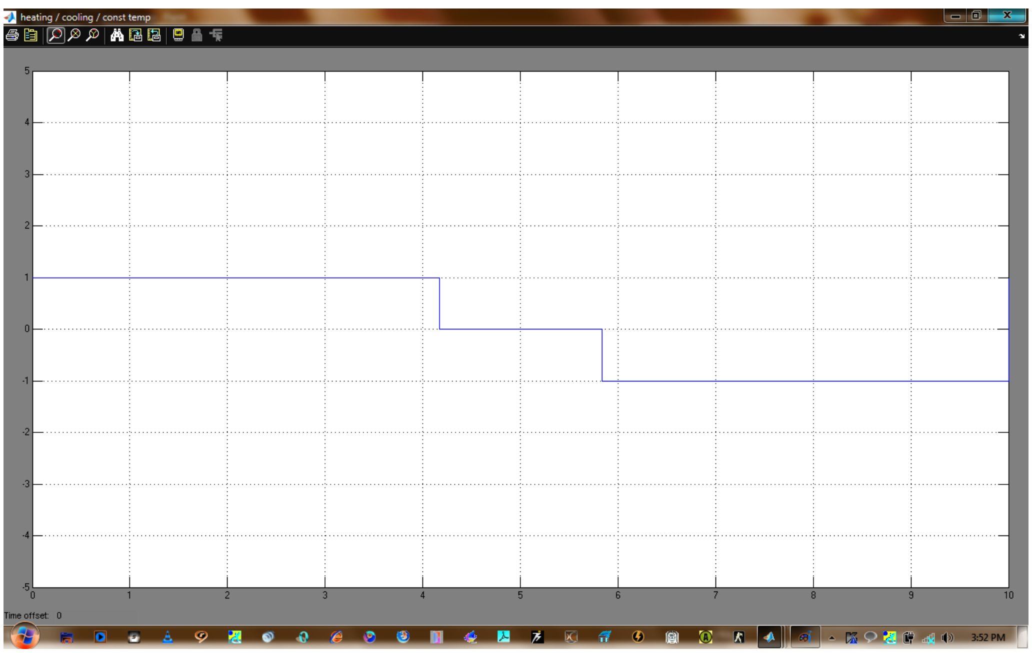

Fig 9. Temperature action as selected by the controller

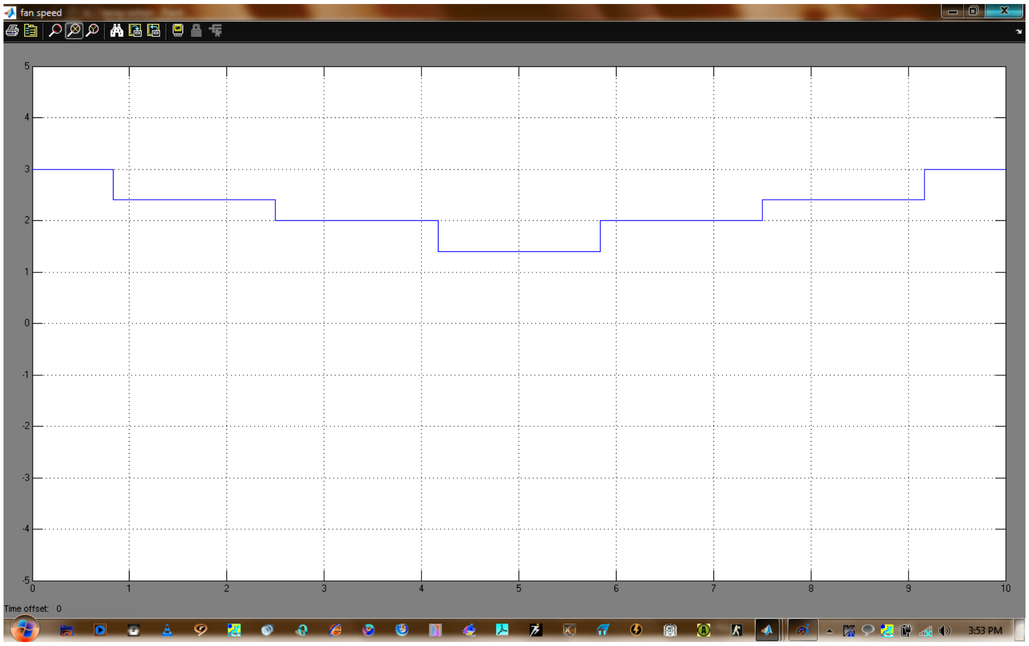

Fig 10. Speed if the Fan as selected by controller as selected by controller

5.1.2Response of the system for the test input of temperature

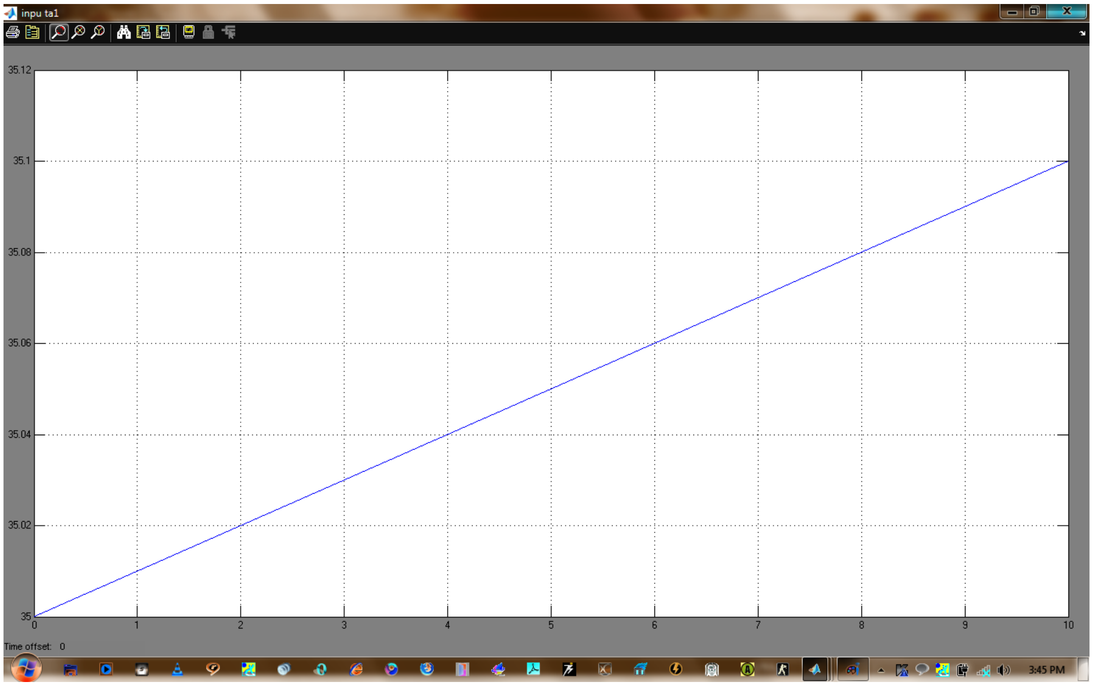

Fig 11. Temperature (outside) variation for a small period of time

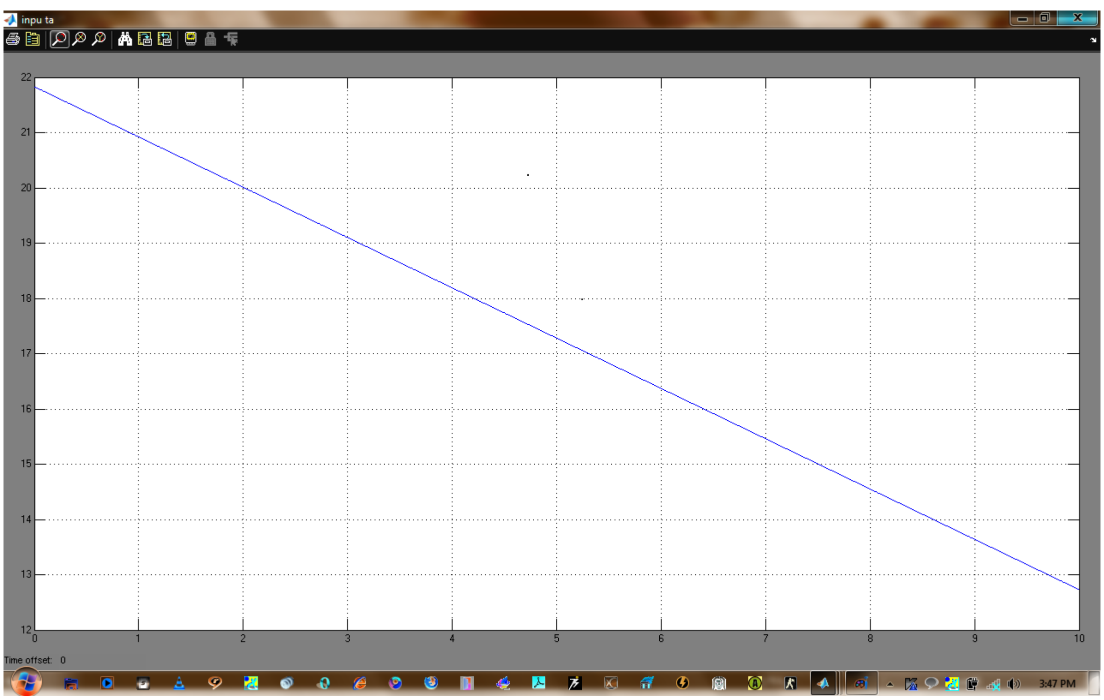

Fig 12. Test input: Change in air temperature

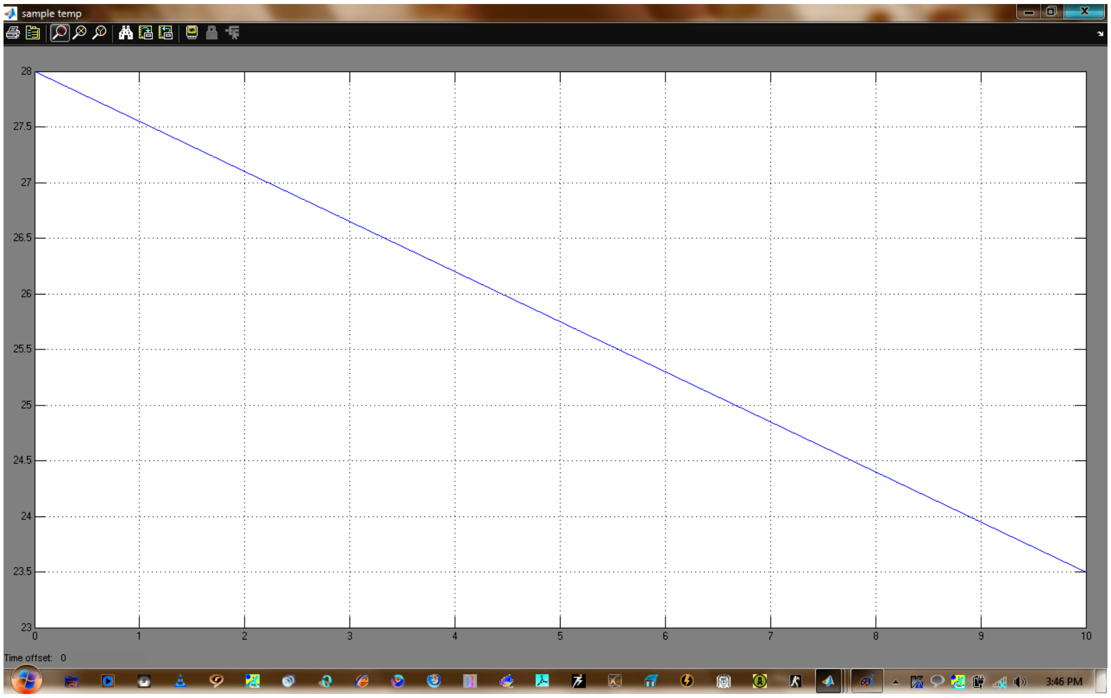

Fig 13. Reference temperature calculated corresponding to the outside temperature

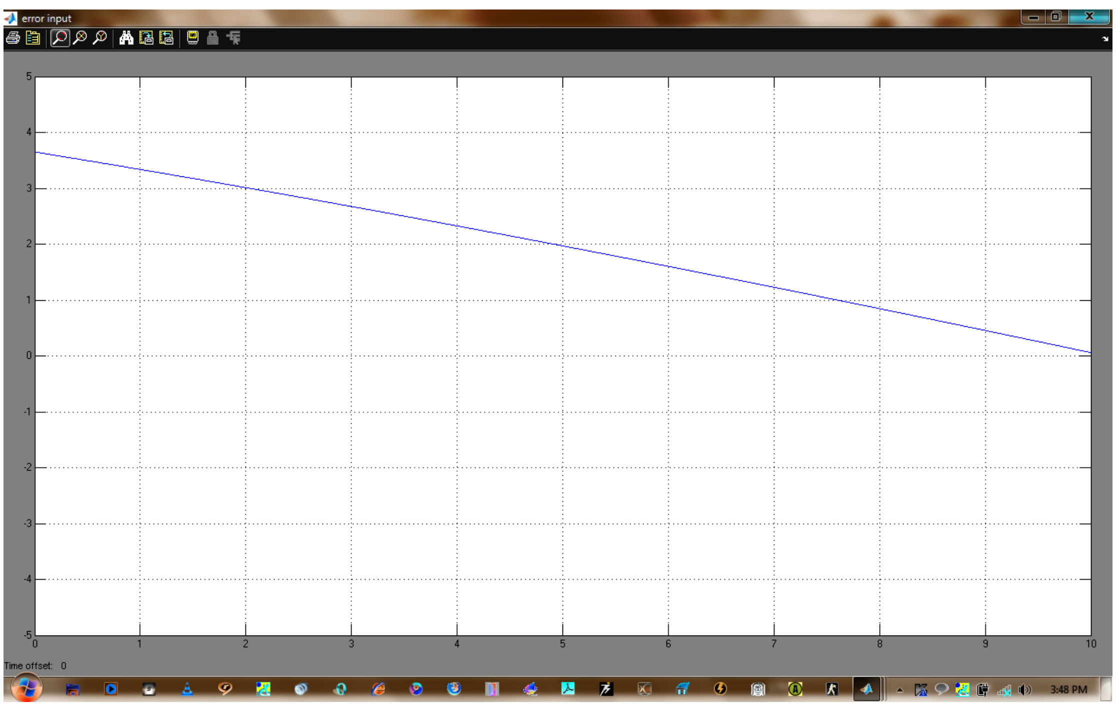

Fig 14. PMV error as calculated by the controller

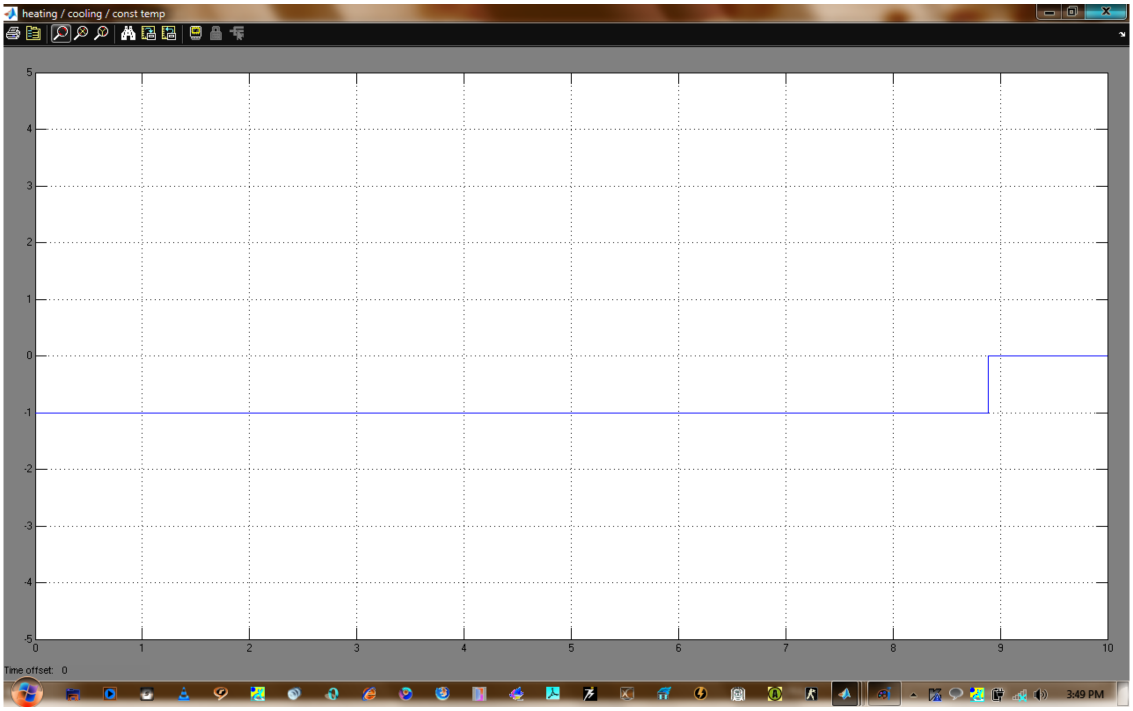

Fig 15. Temperature response as selected by the system

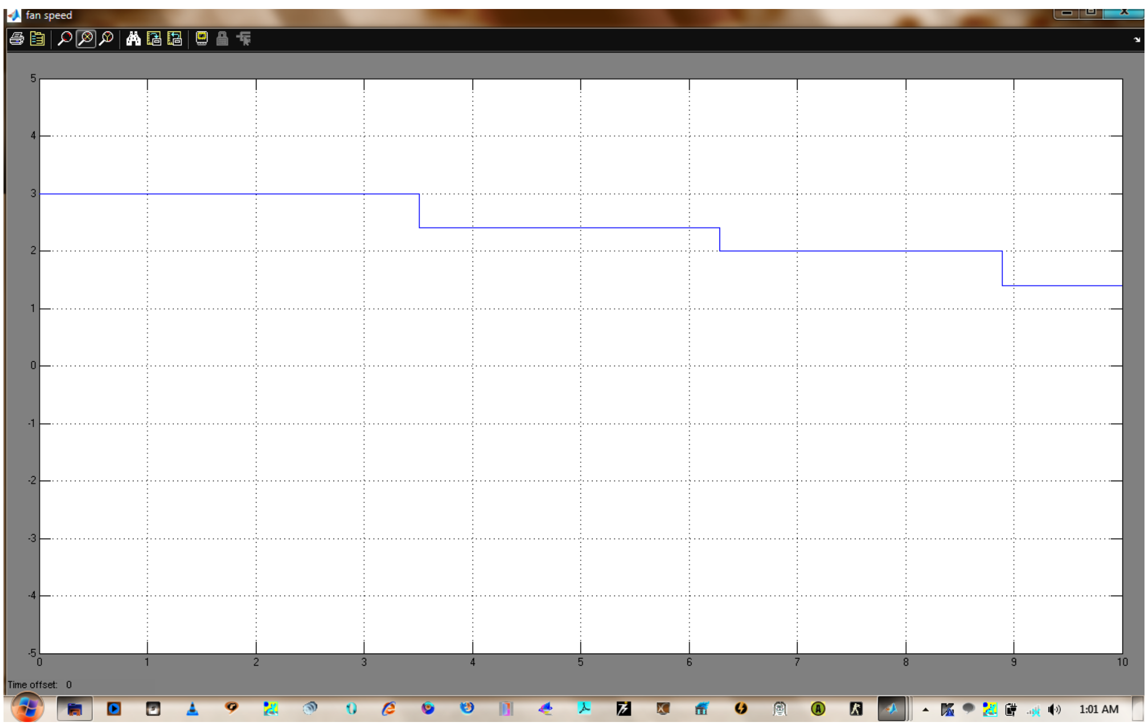

Fig 16. Fan speed as selected by the system

5.2Results for Model2

5.2.1Response of the system for different values of PMV

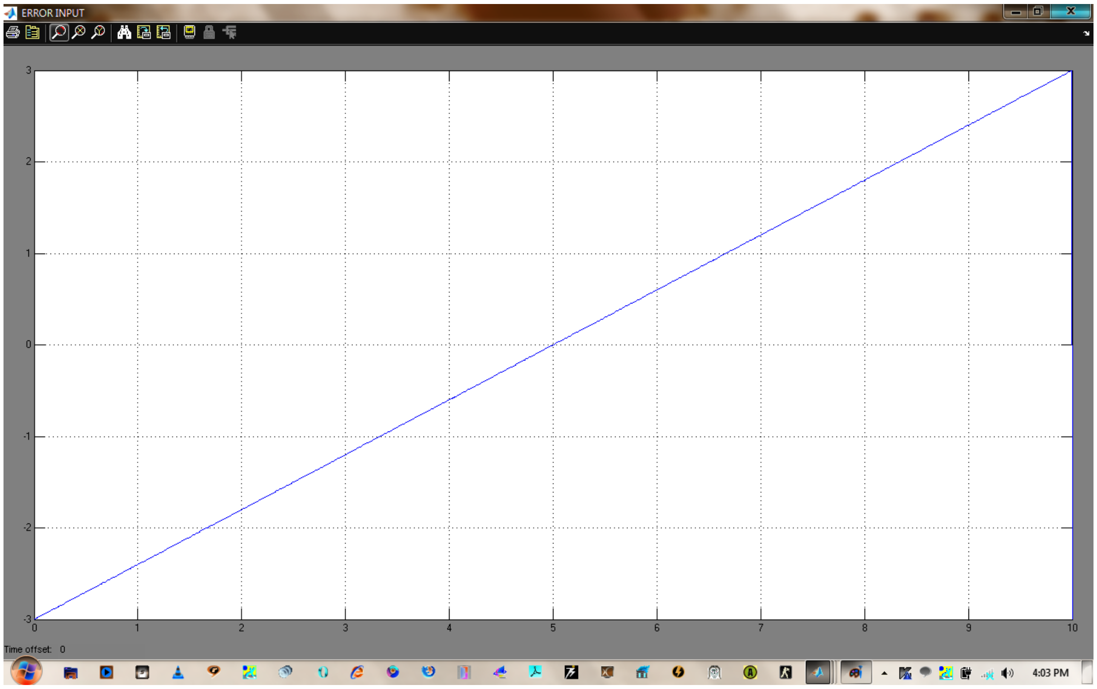

Fig 17. Test inputs: PMV error

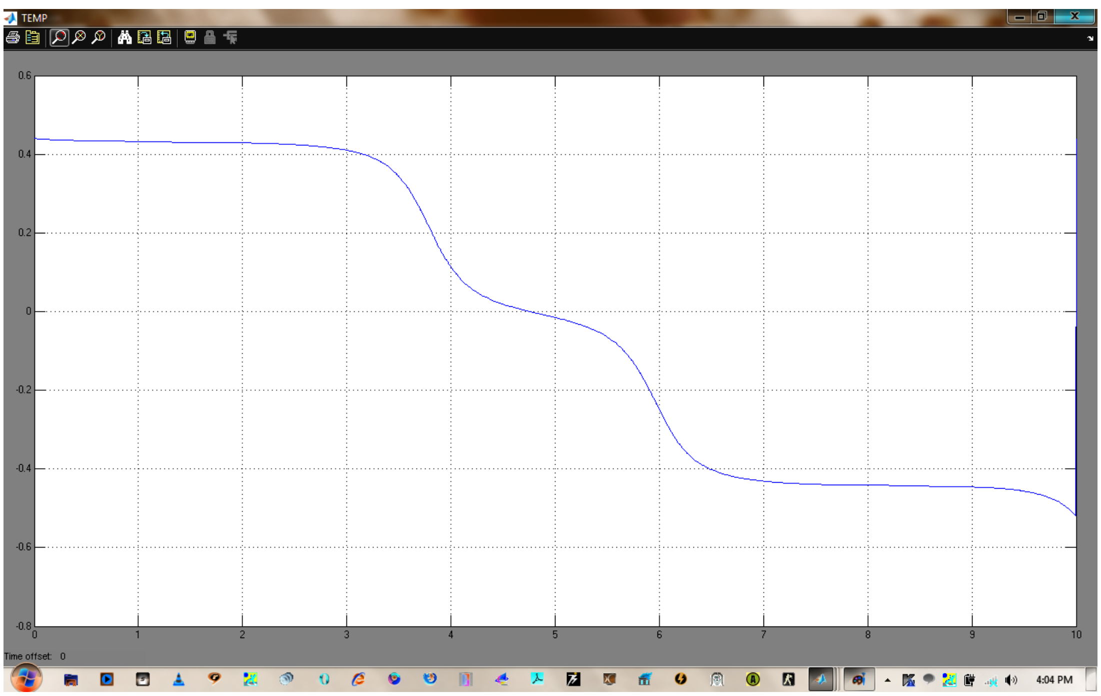

Fig 18. Temperature response as selected by the controller

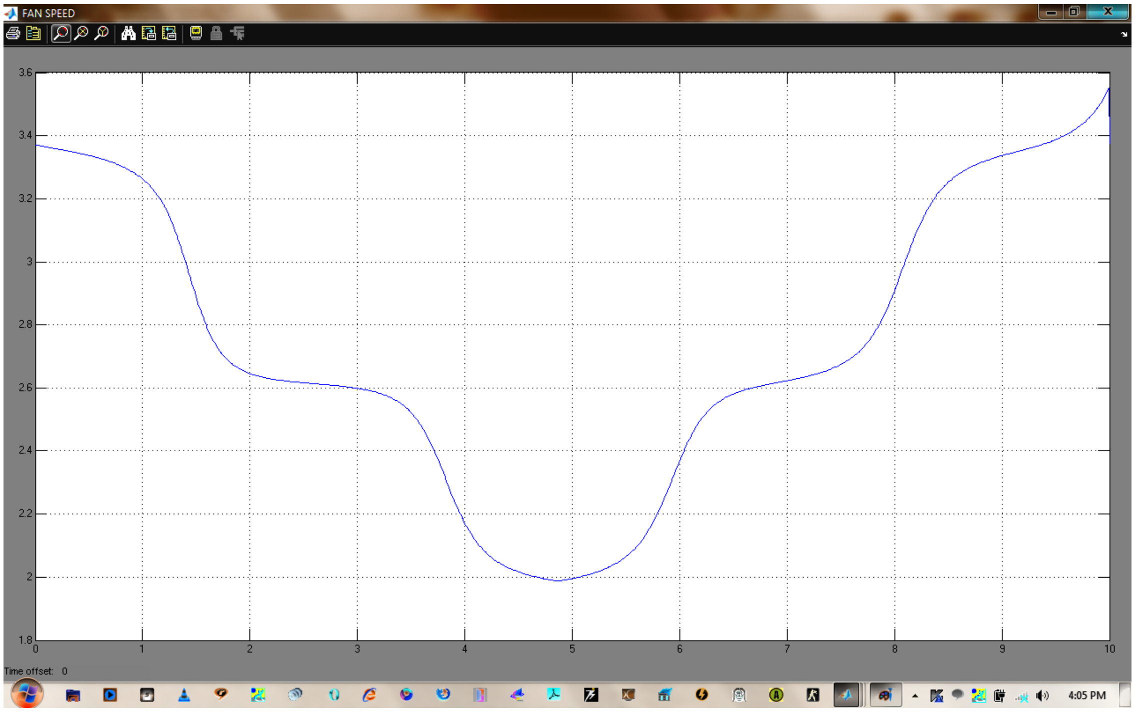

Fig 19. Fan speed the system as selected by the controller

5.2.2Response of the system for test input of temperature

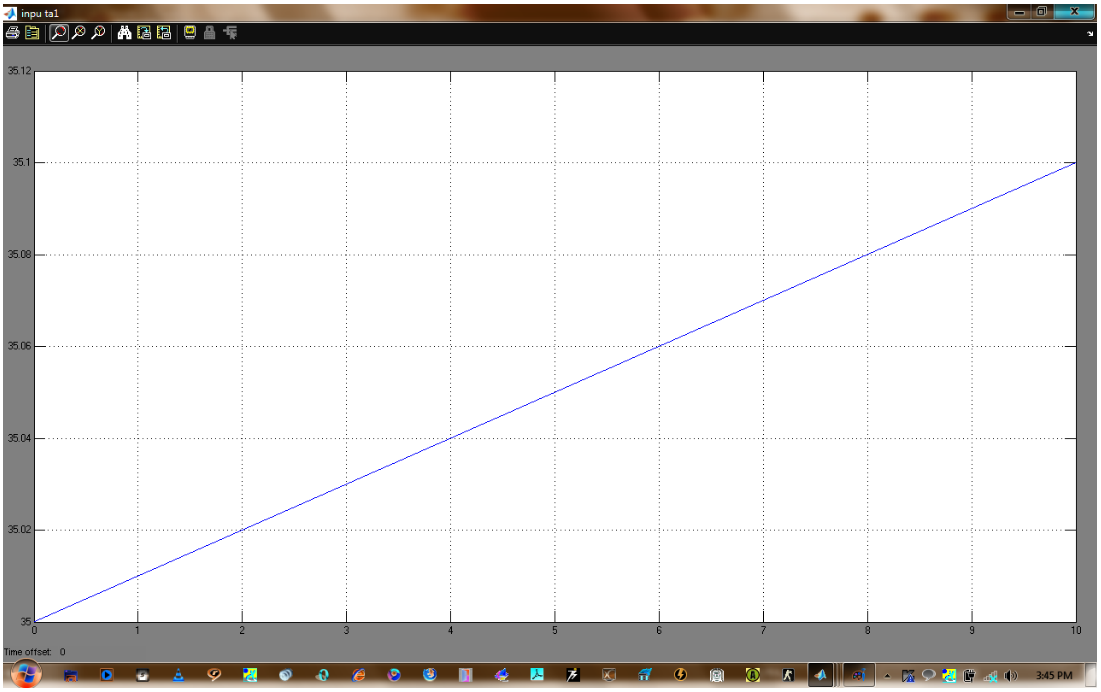

Fig 20. Temperature change for a small period

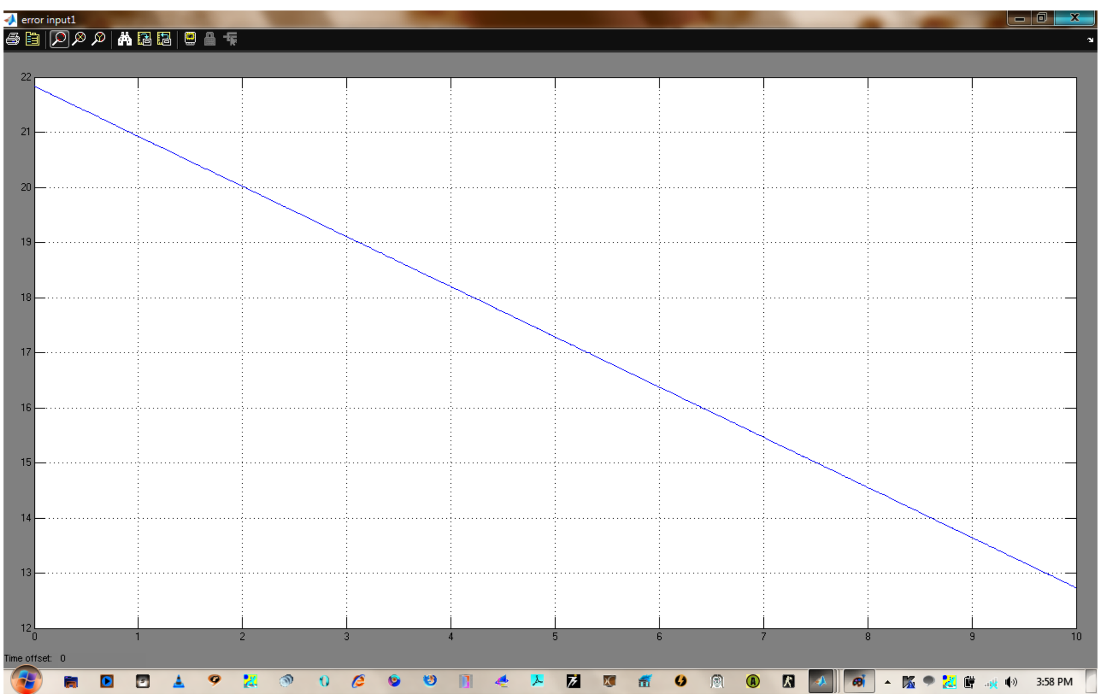

Fig 21. Test input: Change in temperature of the air

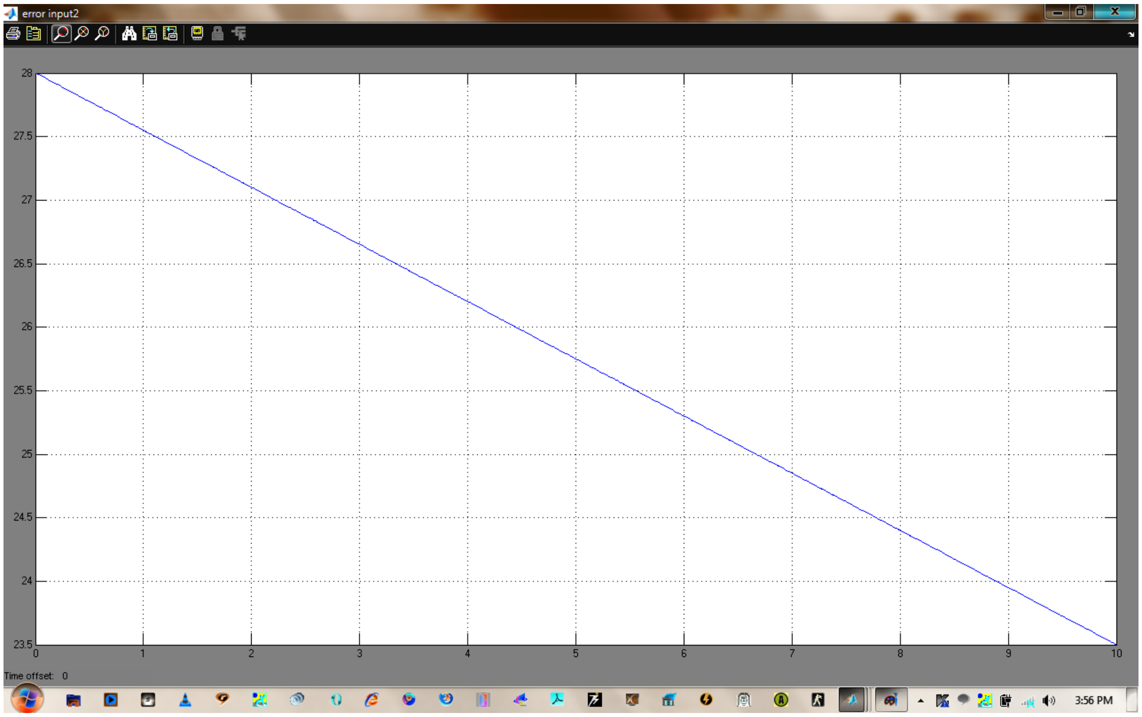

Fig 22. Reference temperature as calculated

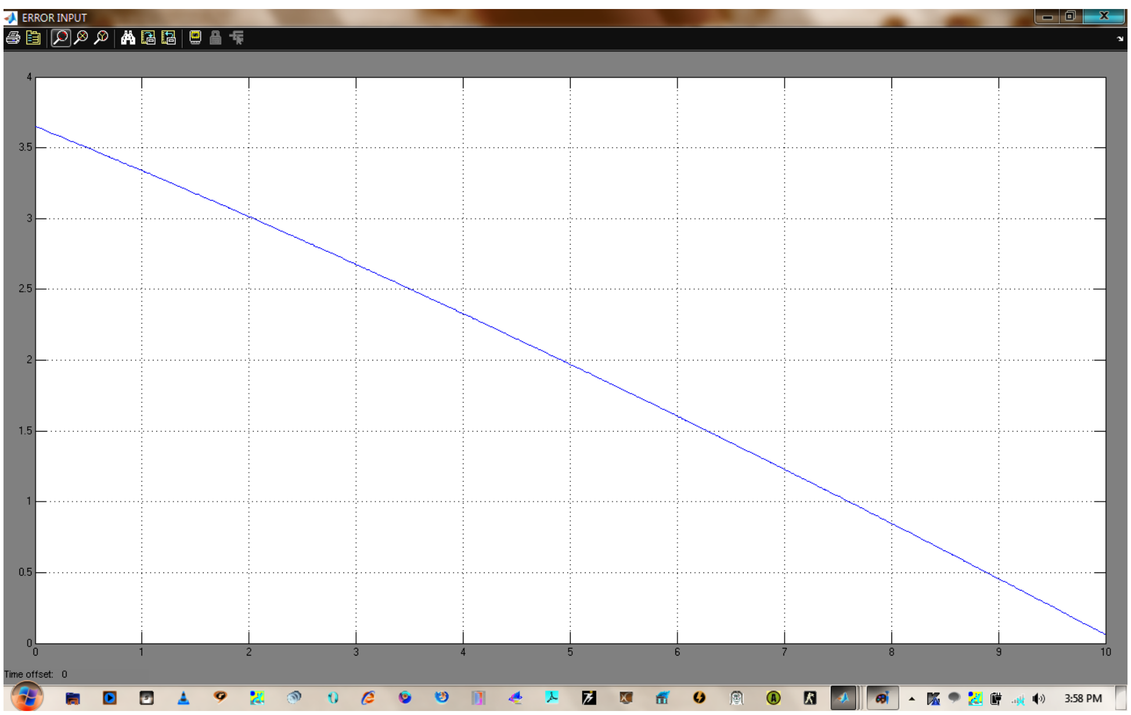

Fig 23. PMV Error as calculated by the controller

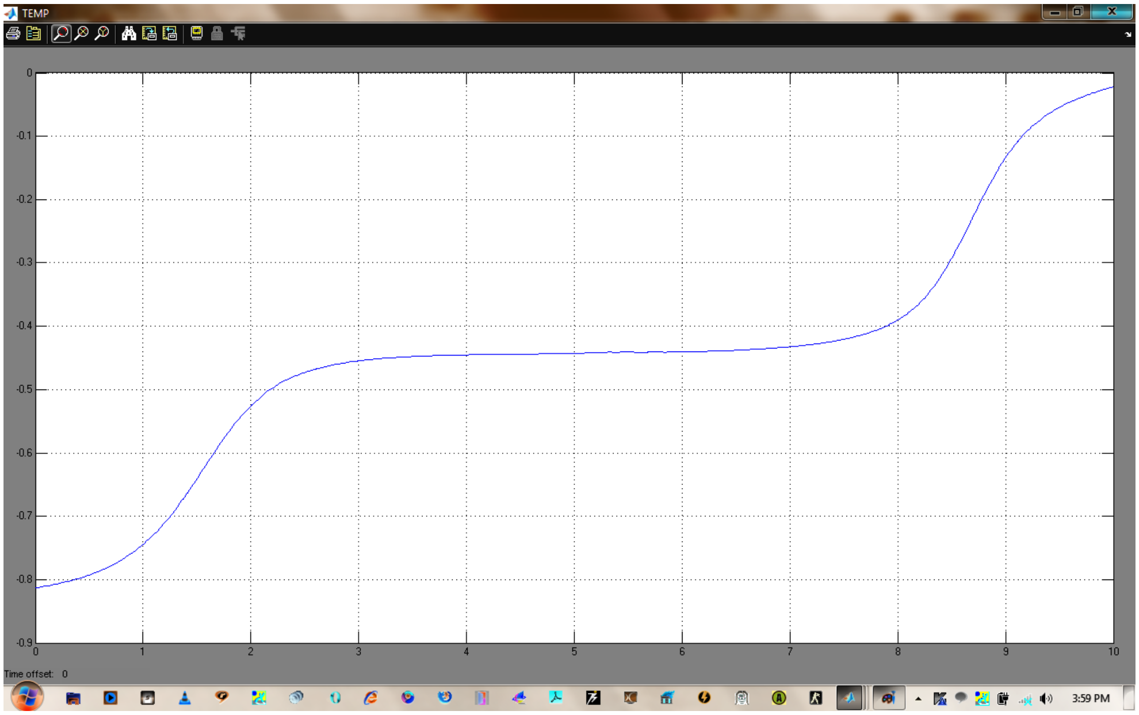

Fig 24. Temperature response as calculated by the controller

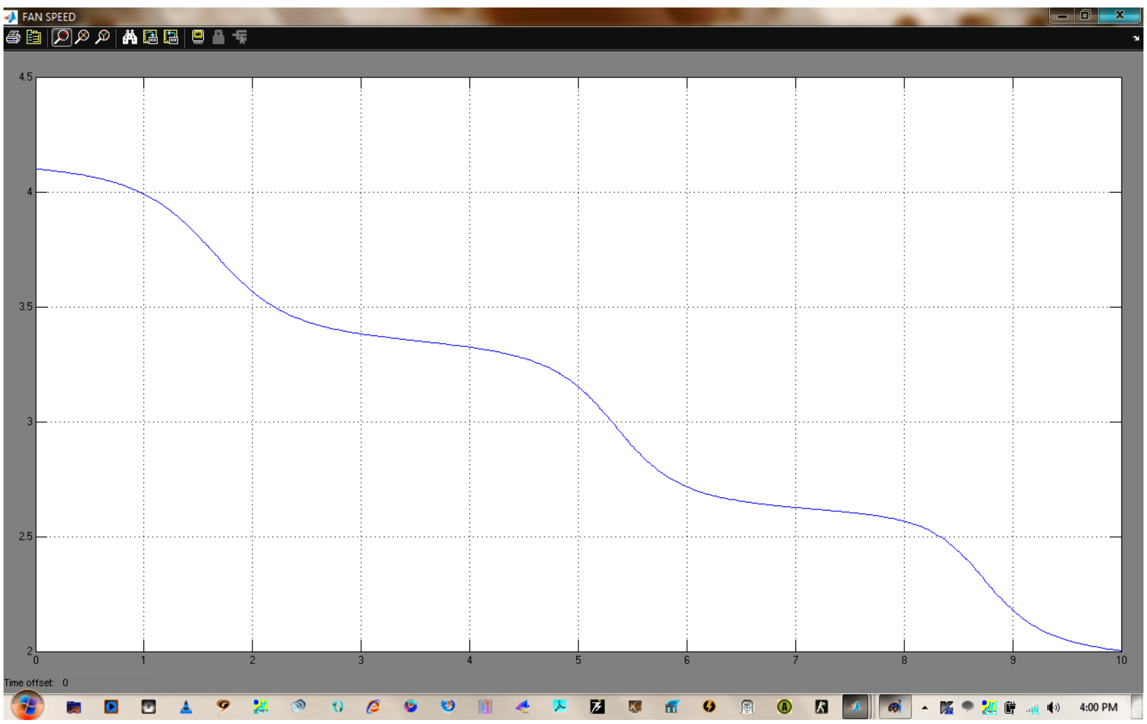

Fig 25. Fan speed as selected by controller

5.3 Results for model3

5.3.1 Response of the system for temperature test input 1

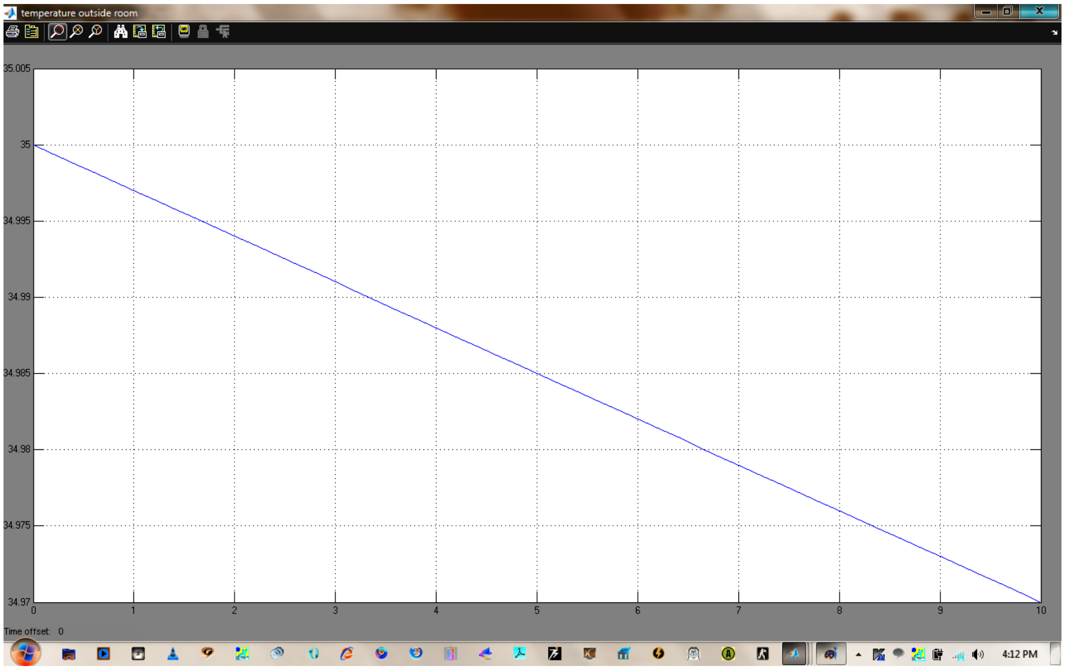

Fig 26. Change in temperature for a small time

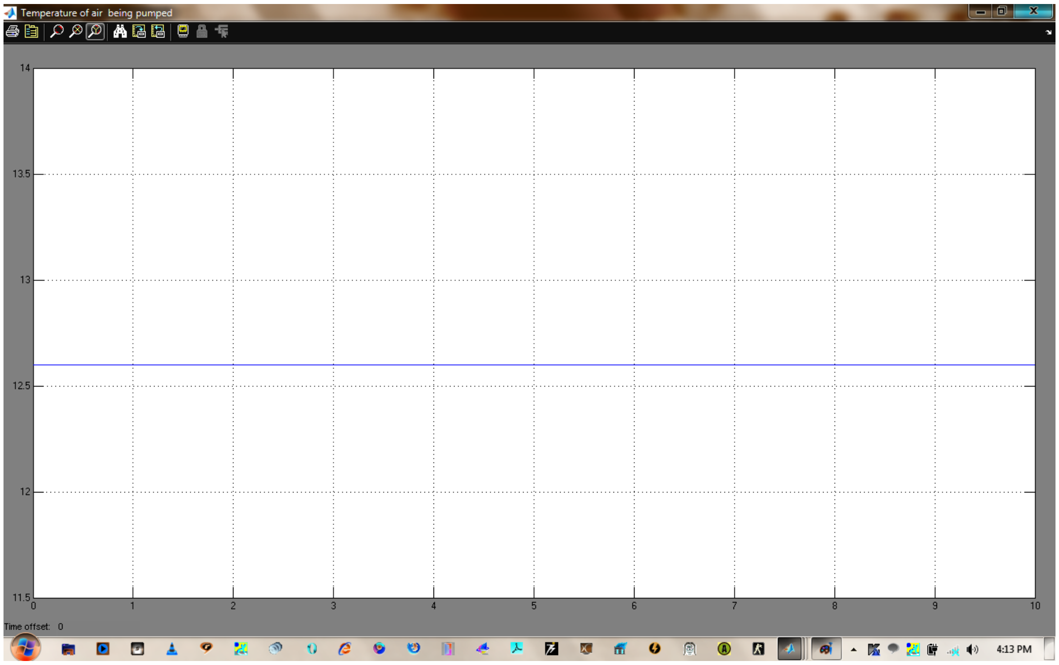

Fig 27. Temperature of air as selected by the controller

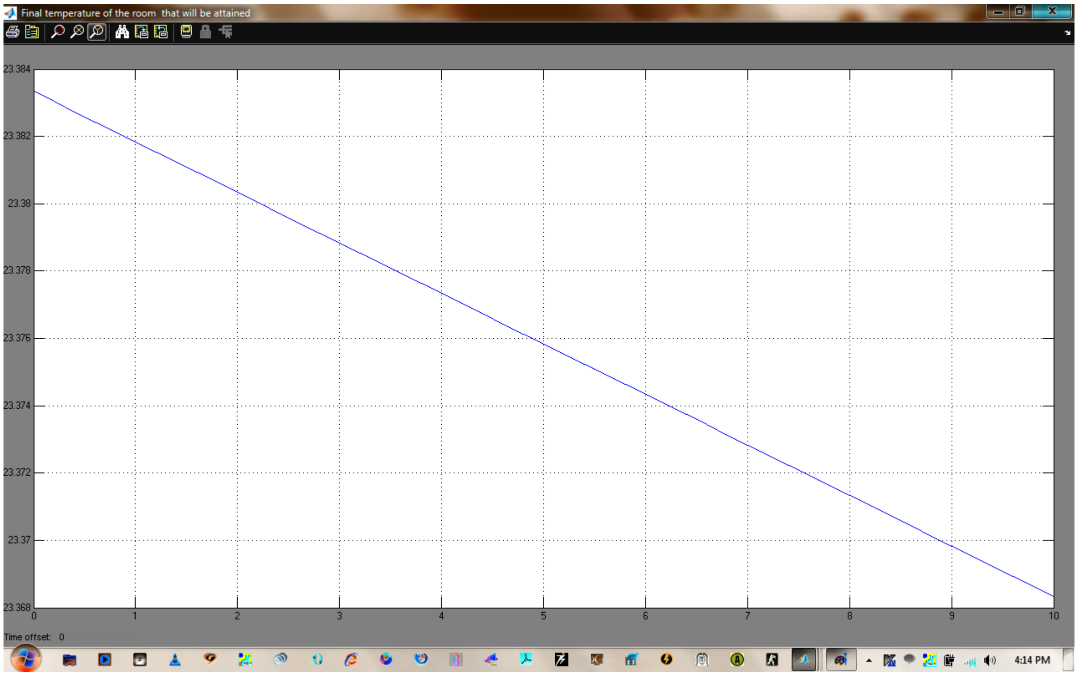

Fig 28. Reference Temperature of the thermal space

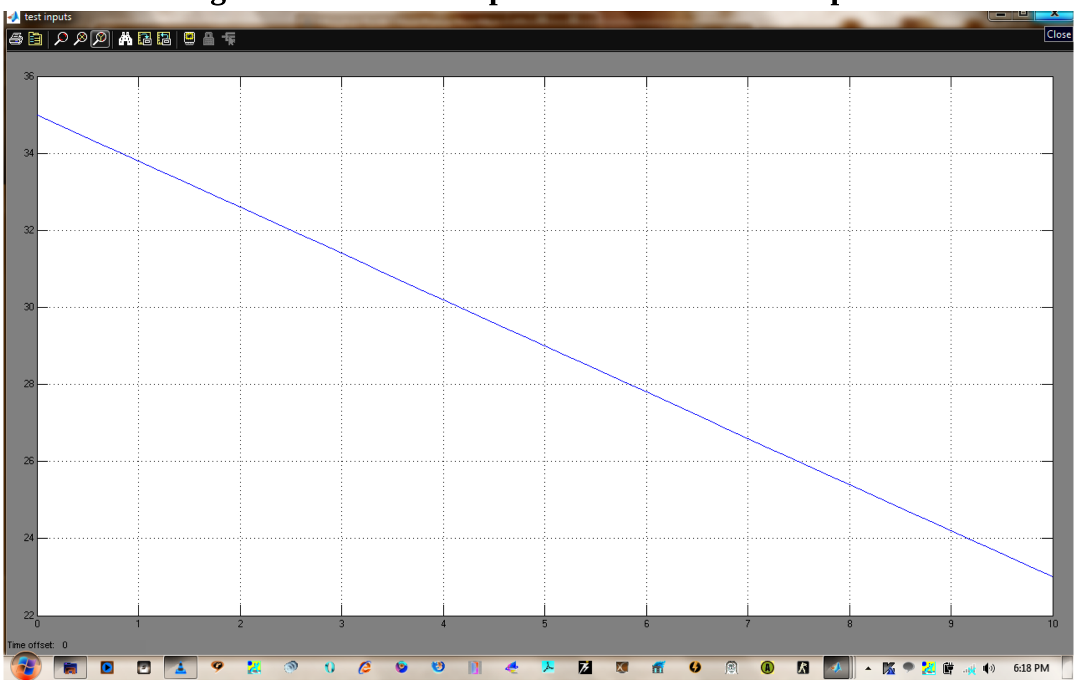

Fig 29. Test input: change in room temperature

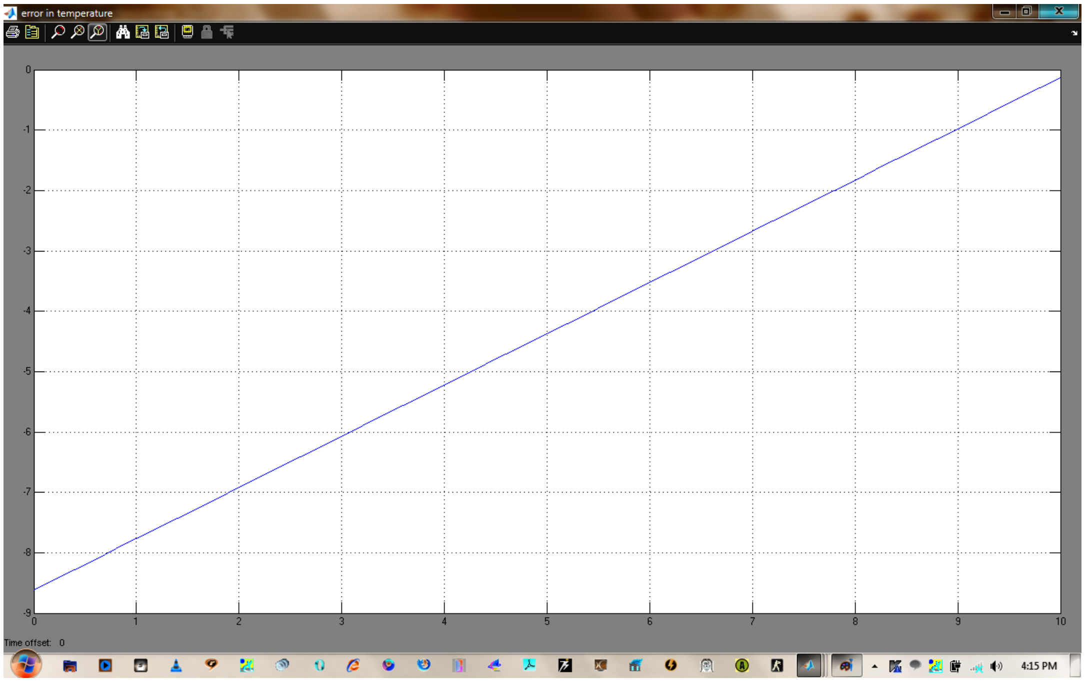

Fig 30. Error in temperature

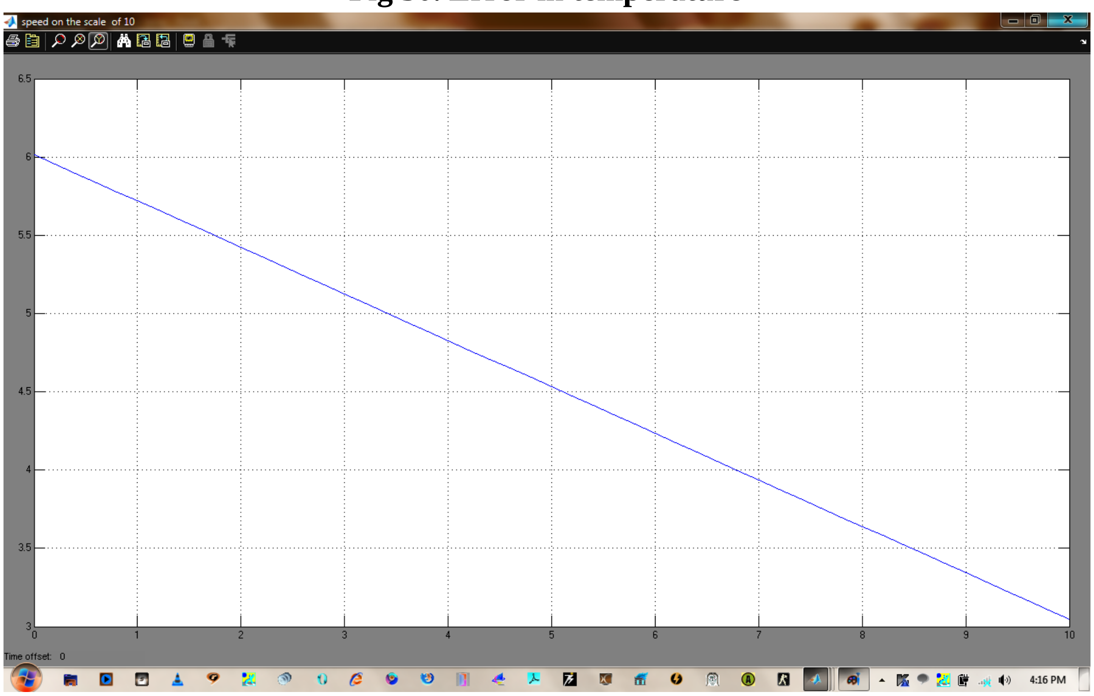

Fig 31. Fan speed as selected by the controller

5.3.2Response of the system for temperature test input 2

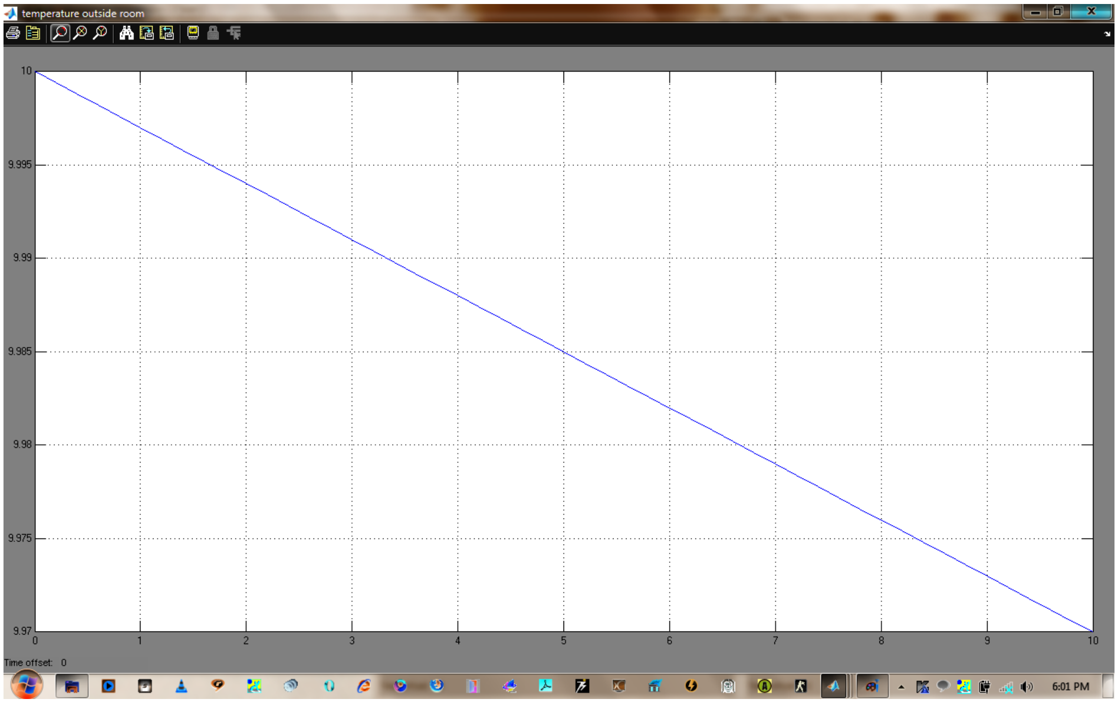

Fig 32. Change in temperature for a small time

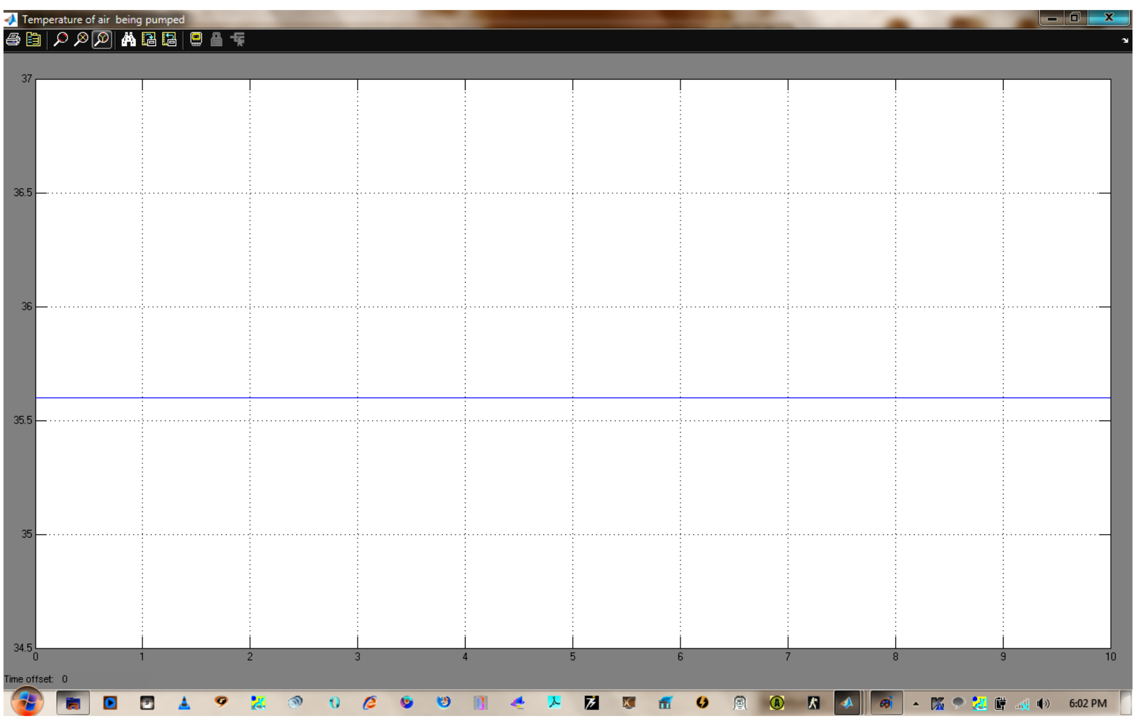

Fig 33. Temperature of air as selected by the controller

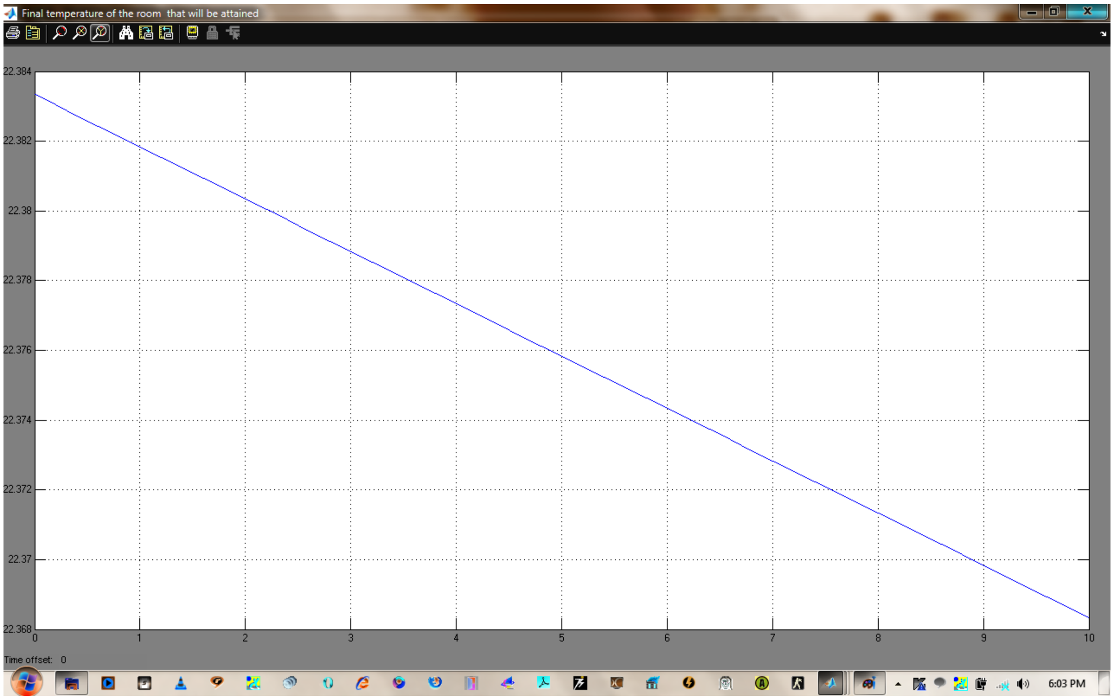

Fig 34. Reference Temperature of the thermal space

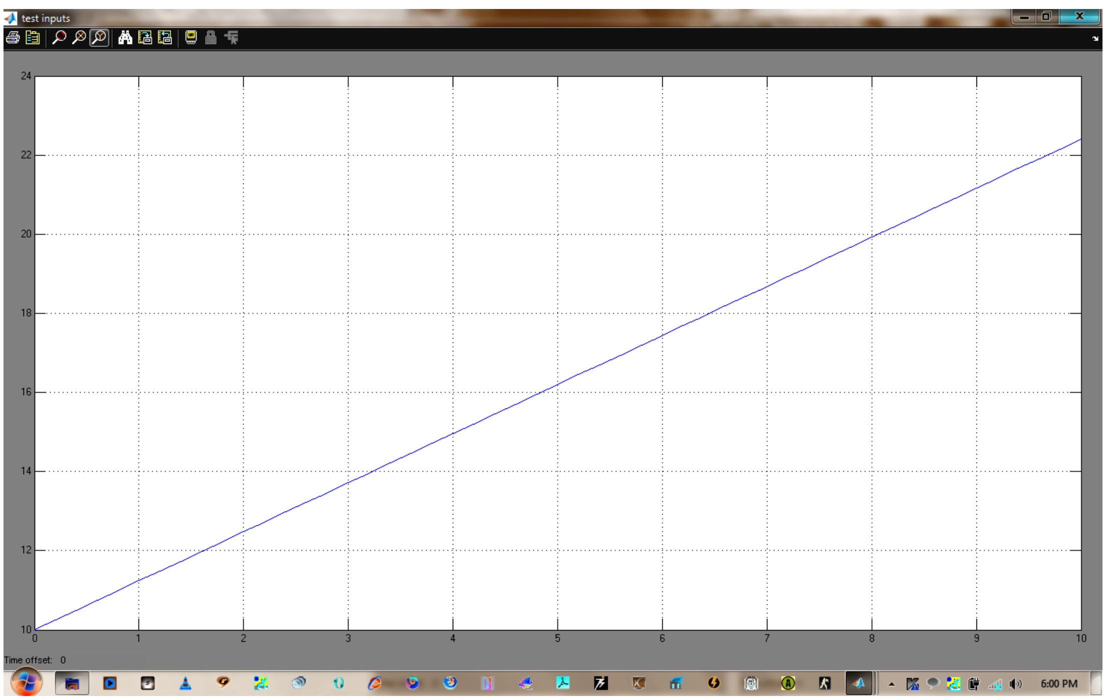

Fig 35. Test input: Change in temperature

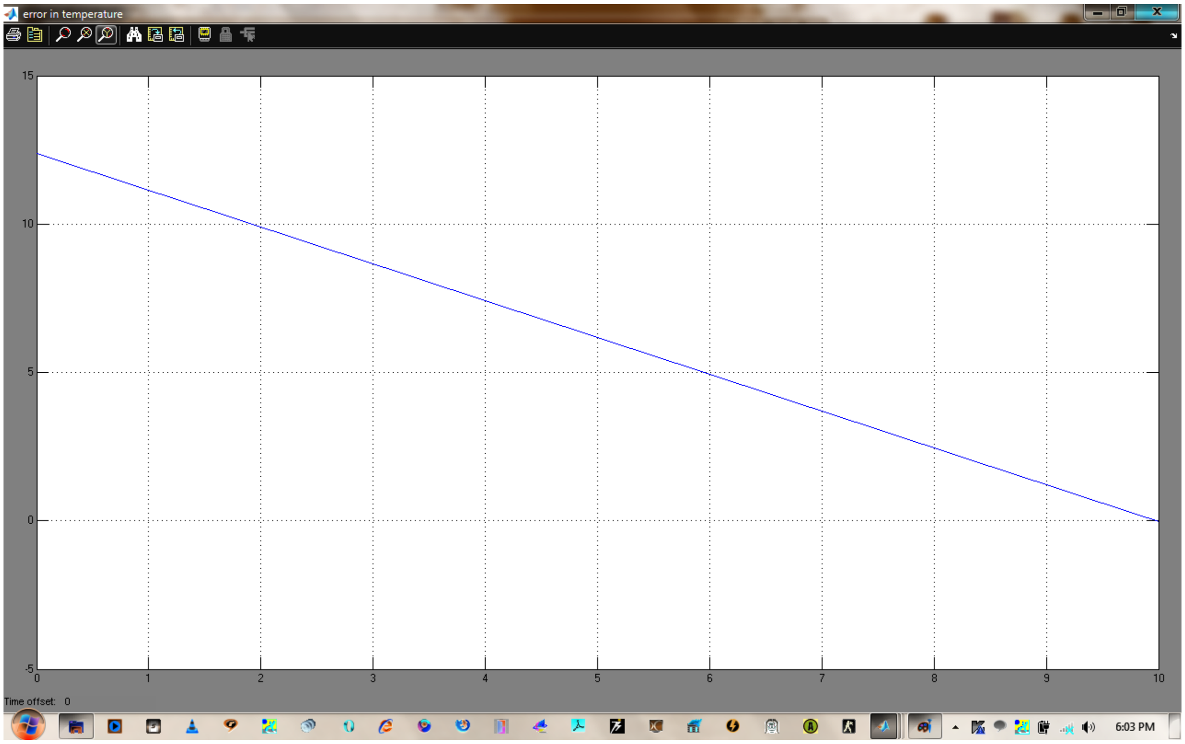

Fig 36. Error in temperature

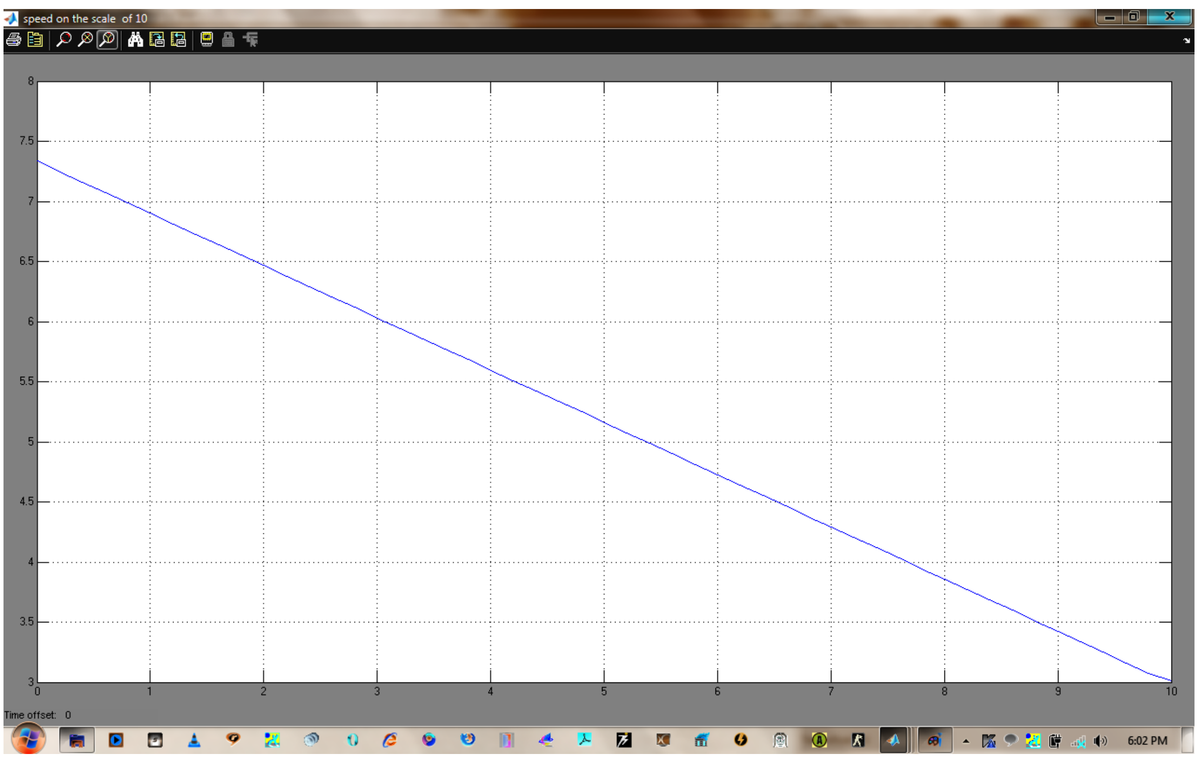

Fig 37. Fan speed as selected by the controller

5.4Comparison

As seen in the above graphs in the results section we can find a contrasting difference in the response of the three models.

1. **Model 1** i.e. the **neural network model** controls the temperature of a thermal space by the variation in the speed of the fan (which in turn controls the volume of the air being pumped in the thermal space) which is decided by the value of the error in PMV calculated and the desired PMV. This factor also controls the decision of the action to be taken i.e. heating or cooling.
2. **Model 2** i.e. the **fuzzy model** controls the temperature in the similar manner as the model 1. But, by the use of the fuzzy model the difference in response can be seen from the graphs shown. The response is much better in case of the fuzzy model as it the model responds differently according to the rule base even for the slightest change in the conditions which is not possible in case of Model 1 because of the quantization involved in case of binary conversion.

   Even though the response is better in case of the fuzzy model but the calculations involved creates the need for a better microprocessor which would increase the cost of the model.
3. **Model 3** is different from Model 1 and Model 2 because it separately calculates the reference temperature for the air and sends it to the HVAC and then on the basis of error between the reference and the measured temperature the speed of the fan is controlled. The reference temperature calculation and the speed control are two separate process and the process of reference temperature can be switched off in case the temperature variation is less than 1 ^{o}C hence saving the power.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

All the three models can be used according to the requirements of the thermal space. Each has their own advantages and disadvantages.

1. Model 1 can be used in places where the quantization in binary calculations do not affect the thermal comfort (i.e. the places where there is very less change in the environmental conditions). But to improve the response of the system the quantization level has to be decreased which requires complex programming and increase in number of calculation which would implementation cost.
2. Model 2 can be used where the temperature control scheme required is same as the model 1 but, response is accurate and sensitivity is more. Due to the use of fuzzy logic the computation time is more as compared to Model 1. Thus the cost of implementation is higher.
3. Model 3 is the model that requires the least amount of calculation. It also consumes less power because of the option of switching the reference temperature calculator off in case of very small temperature change. This model is most efficient when the controller has to function for as long as 24 hrs.

6.2 Future Works

This work only consists of the analysis of all the models. Only the design part has been considered in this work.

In future this work can be tested under various conditions (i.e. by changing the parameters) in order to know the feasibility and the possibility of implementation of the controller in real systems.

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